

# PRODUCTION AND DECAY OF ETA-MESIC NUCLEI

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Using the Green function method, binding effects on produced  $\eta$ -mesons in the two-stage reaction  $\gamma + A \rightarrow N + \eta + (A - 1) \rightarrow N + (\pi N) + (A - 2)$  are studied. The energy spectrum of the correlated  $\pi N$  pairs which arise from decays of  $\eta$ 's inside the nucleus is strongly affected by an attractive  $\eta$ -nucleus optical potential. Its resonant behavior gives a clear signal of forming intermediate  $\eta$ -mesic nuclei.

It was found long ago that the  $S_{11}(1535)$  resonance, which lies above the  $\eta N$  threshold and is strongly coupled to the  $\eta N$  channel, makes the low-energy  $\eta N$  interaction attractive and leads to an existence of bound  $\eta$ -nucleus systems, the so-called  $\eta$ -mesic nuclei.<sup>1</sup> This finding was later confirmed and even strengthened. With contemporary estimates of the  $\eta N$  scattering length,<sup>2,3</sup> the  $\eta$ -mesic nuclei  ${}_{\eta}A$  are expected to exist for all  $A \geq 3$ .<sup>4,5</sup> Studies of the reactions like  $p + d \rightarrow {}^3\text{He} + \eta$  and  $d + d \rightarrow {}^4\text{He} + \eta$  have already provided an experimental evidence that the  $\eta$  and the nucleus in the final state experience a strong attraction which manifests itself in a near-threshold enhancement and in a rapid energy dependence of the cross section.<sup>6,7</sup> Nevertheless, a direct observation of bound rather than free etas would be more convincing for a discovery of  $\eta$ -mesic nuclei. Since the bound  $\eta$  eventually decays through the subprocess  $\eta N \rightarrow \pi N$ , a clear signal for a presence of the stopped etas in nuclei would be in an observation of final pions and nucleons with almost opposite momenta, with the kinetic energies of about 300 MeV and 100 MeV, respectively, and with the total energy close to  $m_{\eta} + m_N$ .<sup>8</sup> In the present work, production of such pairs is studied within a simple model which is aimed at learning how the attraction between the eta and the nucleus affects characteristics of the pairs.

In accordance with the original suggestion,<sup>8</sup> we consider the two-stage reaction

$$\gamma + A \rightarrow N_1 + \eta + (A - 1) \rightarrow N_1 + (\pi N_2) + (A - 2), \quad (1)$$

in which the fast nucleon  $N_1$  knocked out in the subprocess

$$\gamma(k) + N_{\alpha} \rightarrow \eta(E_{\eta}) + N_1 \quad (2)$$

escapes from the nucleus, whereas the  $\eta$  collides with another nucleon  $N_{\beta}$  in the nucleus and perishes producing a pair which also escapes:

$$\eta + N_{\beta} \rightarrow \pi + N_2. \quad (3)$$

Considering the rest of the nucleus as frozen, we write the matrix element of (1) as

$$T_{\alpha\beta} = F_\gamma(k)F_\eta(E_\eta) \iint e^{i\vec{k}\vec{r}_1} \psi_\alpha(\vec{r}_1) \psi_{N_1}^{(-)*}(\vec{r}_1) \times \\ \psi_\beta(\vec{r}_2) \psi_\pi^{(-)*}(\vec{r}_2) \psi_{N_2}^{(-)*}(\vec{r}_2) G(\vec{r}_1, \vec{r}_2; E_\eta) d\vec{r}_1 d\vec{r}_2. \quad (4)$$

Here  $\psi_\alpha, \psi_\beta$  are the wave functions of the bound nucleons with the binding energies  $\epsilon_\alpha, \epsilon_\beta$  and  $\psi_{N_1}, \psi_{N_2}, \psi_\pi$  are the wave functions of the final particles.  $F_\gamma, F_\eta$  are the amplitudes of the reactions (2) and (3) which, at energies considered, are approximated by  $s$ -waves. The Green function  $G$  gives the amplitude of  $\eta$  with the energy

$$E_\eta = E_\gamma + \epsilon_\alpha - E_{N_1}^{\text{kin}} = E_\pi + E_{N_2}^{\text{kin}} - \epsilon_\beta \quad (5)$$

to propagate from  $\vec{r}_1$  to  $\vec{r}_2$  in the mean field  $V(r)$  of the intermediate nucleus  $(A-1)$  which can be assumed to be independent on  $\alpha$ . In the following we also neglect the dependence of  $E_\eta$  on the hole states  $\alpha, \beta$  and replace  $\epsilon_\alpha, \epsilon_\beta$  by their Fermi-gas average  $\langle\epsilon\rangle \simeq -23$  MeV.

When a single bound state  $\psi_0$  of the (complex) energy  $E_0$  dominates, the Green function takes the separable form

$$G(\vec{r}_1, \vec{r}_2; E_\eta) \simeq \frac{\psi_0^+(\vec{r}_1) \psi_0(\vec{r}_2)}{E_\eta^2 - E_0^2}, \quad (6)$$

which results in the Breit-Wigner resonant behavior of the pair production through the intermediate  $\eta$ -mesic nucleus. In such an approximation, the amplitude (4) depends on the overlap of  $\psi_0(r)$  with the nucleus's nucleons and typically the total cross section of the  $\eta$ -mesic nucleus formation by photons is 5–10  $\mu\text{b}$  for  $A = 12$  to 16.<sup>9</sup> With the realistic optical potential strength, however, there are several bound states of  $\eta$  which are strongly overlapped and act coherently. Also, there is a non-resonance background which describes the process  $\gamma \rightarrow \eta \rightarrow \pi$  in the nucleus with unbound etas. For these reasons Eq. (6) is generally insufficient and the full Green function has to be used to describe the reaction (1).

As an illustration of what may happen, we discuss here the spectral function<sup>10</sup>

$$S(E_\eta) = \iint \rho(\vec{r}_1) \rho(\vec{r}_2) |G(\vec{r}_1, \vec{r}_2; E_\eta)|^2 d\vec{r}_1 d\vec{r}_2, \quad (7)$$

which describes a global nuclear dependence of the matrix element (4) squared and averaged over the nuclear states and momenta of the outgoing particles.

$S(E_\eta)$  characterizes the nuclear dependence of the total cross section of the two-step transition  $\gamma \rightarrow \eta \rightarrow \pi$  in nuclei. It is proportional to the number of nucleons hit by  $\eta$ 's produced somewhere inside the nucleus. This number increases when the  $\eta$  has the energy close to a resonance level; such  $\eta$ 's are captured by the nucleus and pass a few times across the nucleus before they annihilate or escape.

In actual calculations of  $G$  and  $S(E_\eta)$  we use the simple first-order energy-dependent potential  $2E_\eta V(r, E_\eta) = -(4\pi\sqrt{s}/M_N)f_{\eta N}(E_\eta)\rho(r)$  with the  $\eta N$  scattering amplitude taken from Ref.<sup>3</sup> and with the square-well nuclear density  $\rho(r) = 0.75\rho_0$  at  $r < R_A$ ,  $R_A = 1.2A^{1/3}$  fm. Such a potential gives the energy of the ground state and its width  $\Gamma$  close to those found in a recent analysis<sup>11</sup>. Typically, the widths are  $\Gamma \sim 20$  MeV and far less than those found in an older work<sup>12</sup> which seems to overestimate<sup>11</sup> the width's broadening due to the two-nucleon absorption  $\eta NN \rightarrow NN$  in the nucleus.

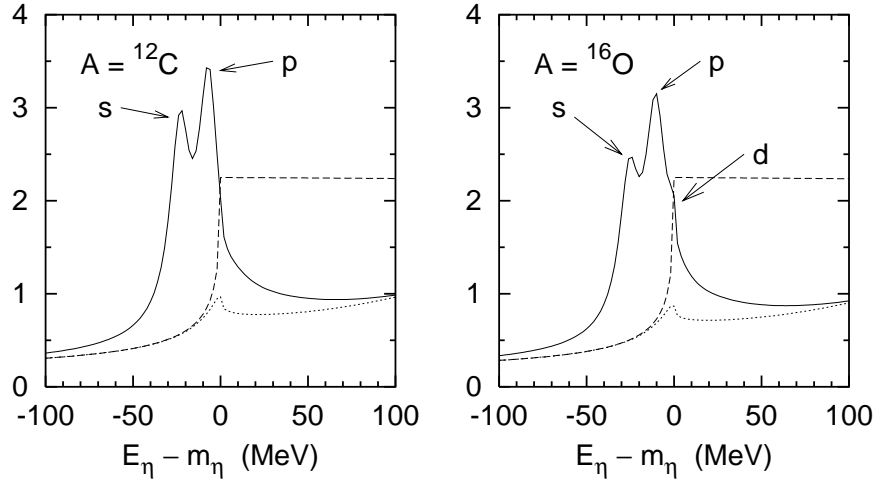


Figure 1: The normalized spectral function  $\bar{S}(E_\eta) = (16\pi^2 R_A^2/A^2)S(E_\eta)$  for the square-well potential representing the carbon and oxygen. Dashed lines: the optical potential is switched off; then  $\bar{S}(E_\eta) = \frac{9}{4}$  above the  $\eta$  threshold. Dotted lines: the absorption  $\text{Im } V(r)$  is on. Solid lines: both the attraction  $\text{Re } V(r)$  and the absorption  $\text{Im } V(r)$  are on. The resonance-like structures are composed of  $s$ ,  $p$ ,  $d$  resonances in the  $\eta$ -nucleus system.

In the absence of the potential  $V(r)$ , the Green function reads  $G = e^{iqr}/(4\pi r)$ , where  $r = |\vec{r}_1 - \vec{r}_2|$  and  $q^2 = E_\eta^2 - m_\eta^2$ . Accordingly,  $S(E_\eta)$  does not depend on  $E_\eta$  when  $E_\eta > m_\eta$ . At sub-threshold energies, when  $\eta$  cannot propagate far from the production point,  $S(E_\eta)$  rapidly vanishes. When the

absorptive part  $\text{Im } V(r)$  of the optical potential is taken into account,  $S(E_\eta)$  falls down as well. However, it strongly enhances when the attraction  $\text{Re } V(r)$  is on and the bound states appear. In fact, the resonance-like structure of  $S(E_\eta)$  consists of many  $s, p, d, \dots$  wave contributions. See Fig. 1.

The practically important finding is that the non-resonance background in  $S(E_\eta)$  is relatively small, so that most of produced  $\pi N$  pairs with near-threshold energies appear from the decay of the resonant  $\eta$ -mesic states. Due to the spread in the separation energies  $\epsilon_\alpha, \epsilon_\beta$ , the inclusive distribution of the total energy  $E_\pi + E_{N_2} = E_\eta + m_N + \epsilon_\beta$  of the pairs is smeared and rather exhibits a single giant peak of the width  $\Gamma \sim 40\text{--}50$  MeV. Such pairs have been recently observed in the experiment performed at Lebedev Institute.<sup>13</sup> Further analysis of their energy distribution may hopefully reveal whether the  $\eta$ -mesic nuclei were really found.

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## References

1. Q. Haider and L. Liu, *Phys. Lett. B* **172**, 257 (1986); *Phys. Rev. C* **34**, 1845 (1986).
2. M. Batinic *et al.*, nucl-th/9703023.
3. A.M. Green and S. Wycech, *Phys. Rev. C* **55**, R2167 (1997).
4. S.A. Rakityansky *et al.*, *Phys. Rev. C* **53**, R2043 (1996); S.A. Sofianos and S.A. Rakityansky, nucl-th/9707044.
5. V.A. Tryasuchev, *Yad. Fiz.* [English transl.: Physics of Atomic Nuclei] **60**, 245 (1997).
6. C. Wilkin, *Phys. Rev. C* **47**, R938 (1993).
7. N. Willis *et al.*, *Phys. Lett. B* **406**, 14 (1997).
8. G.A. Sokol and V.A. Tryasuchev. *Kratkie Soobsh. Fiz.* [English transl.: Sov. Phys. – Lebedev Institute Reports] **4**, 23 (1991).
9. A.I. Lebedev and V.A. Tryasuchev, *Yad. Fiz.* **58**, 642 (1995); A.I. L’vov, in preparation.
10. O. Morimatsu and K. Yazaki, *Nucl. Phys. A* **435**, 727 (1985); **A 483**, 493 (1988).
11. J. Kulpa, S. Wycech and A.M. Green, nucl-th/9807020.
12. H.C. Chiang, E. Oset and L.C. Liu, *Phys. Rev. C* **44**, 2595 (1988).
13. G.A. Sokol *et al.*, talk at the 14th Int. Seminar on High Energy Physics Problems, 17–22 August 1998, Dubna; to appear in proceedings.